

**Close out and Final report for
NASA Glenn Cooperative Agreement NCC3-863**

Lifing of Engine Components

Research Scope

The successful development of advanced aerospace engines depends greatly on the capabilities of high performance materials and structures. Advanced materials, such as nickel based single crystal alloys, metal foam, advanced copper alloys, and ceramics matrix composites, have been engineered to provide higher engine temperature and stress capabilities. Thermal barrier coatings have been developed to improve component durability and fuel efficiency, by reducing the substrate hot wall metal temperature and protecting against oxidation and blanching. However, these coatings are prone to oxidation and delamination failures. In order to implement the use of these materials in advanced engines, it is necessary to understand and model the evolution of damage of the metal substrate as well as the coating under actual engine conditions. The models and the understanding of material behavior are utilized in the development of a life prediction methodology for hot section components. The research activities were focused on determining the stress and strain fields in an engine environment under combined thermo-mechanical loads to develop life prediction methodologies consistent with the observed damage formation of the coating and the substrates.

Objective

The objective of this research was to determine the failure mode of various engine components under engine simulated loading conditions. The research effort was intended to analytically complement the experimental programs currently being conducted at NASA-Glenn in the Life Prediction Branch of the Structure and Acoustic Division for various NASA programs.

A summary of key findings for the various work elements are provided below. Finally a list of papers and presentations prepared throughout the duration of this cooperate agreement is appended at the end.

Work Element Summary

Optimize the Design of New Generation Turbine Disk

A study was conducted to optimize the design of a turbine disk. A finite difference scheme was programmed to determine the temperature and stress distribution in a rotating disk with a variable thickness. The differential equation for the radial displacement was formulated based on the force equilibrium as a function of radial distance and variable thickness and temperature. Solutions for the radial and hoop stresses are easily performed for a given disk thickness profile, rotational speed, temperature profile, and inner and outer pressure. The formulation was compared with available solutions in the literature as well as the finite element method. The same formulation is used for a solid or hollow disk. Preliminary design optimization was able to reduce the stresses by 44% for a solid disk versus existing design for the T-700 second stage disk

with a 2% increase in weight. An optimum disk profile was able to reduce the weight by about 30% and also reduce the stresses by 5% compared to current T-700 disk.

Reliable engine-weight estimation at the conceptual design stage is critical to the development of new aircraft engines. It helps to identify the best engine concept amongst several candidates. Major enhancements to NASA's engine-weight estimate computer code included the incorporation of improved weight-calculation routines for the compressor and turbine disks using the finite-difference technique. Furthermore, the stress distribution for various disk geometries was also incorporated, for a life-prediction module to calculate disk life. A material database, consisting of the material data of most of the commonly-used aerospace materials, has also been incorporated into the WATE code. Collectively, these enhancements provide a more realistic and systematic way to calculate the engine weight. They also provide additional insight into the design trade-off between engine life and engine weight.

Transient Heat-Transfer and Stress Analysis for a Pulse Detonation Combustor

Transient heat transfer and stress analysis were conducted in support of the Pulse Detonation Engine program. The thermal shock induced during engine pulsing is detrimental for the combustor material. The temperature profile was determined a function of time under a 61 Hz pulsating heat wave with a temperature over-peak of 3700C for a 0.2 msec duration. Three classes of combustor materials (Iron Based SS316, Nickel Based IN-601, and Cobalt Based Haynes-188) were used analyzed in the analysis to help select the optimum material for the final design. An optimum liner thickness and cooling flux were obtained for the three materials.

In addition to the combustor design, a modeling of experimental laser heating of various specimens with a heat flux simulating the heat wave in a PDE combustor were also conducted. The temperature and stress distribution are calculated for a rotating fatigue specimen expose to a pulsing laser heating at 100 Hz. The calculated stresses are used to estimate the damage accumulated along the specimen surface after such exposure.

In support of the pulse detonation cooled test bed tube design, modeling of an experimental laser heating bend plate with holes simulating the heat wave was conducted. The temperature and stress distribution are calculated for a 10 Hz bending load as well as the pulsing laser heating at 100 Hz. The calculated thermal induced stresses are used to estimate the additional damage accumulated along the specimen surface due the laser pulsing. The stress concentrations around the holes were calculated under the pulsating laser heat flux for various diameter holes and bending loads. A fracture mechanic analysis was conducted to determine the stress intensity factors for a crack emanating from the hole under tensile and bending stresses. The stress intensity factors were calculated from various diameter holes, crack depth and crack length. These results are used to predict the fracture life of the experimental bend plates.

Determining the Crack Driving Forces in Single Crystal Superalloys

A modeling effort is underway to understand the observed failure mode in single crystal materials under contact loading. This failure model occurs along crystallographic planes under high compressive normal loads. The stress distribution in an anisotropic half plane under an elliptical

surface loading condition was calculated using a green function. The maximum shear stresses along crystallographic planes were calculated for various single crystal orientations. The planes with the maximum shear seem to correlate with the actual failure planes of single crystal blades of the space shuttle hydrogen pump. A second effort was to determine the stress intensity factors for an anisotropic middle tension compression disk as a function of crack orientation and crack length. The crack path will be predicted and compared with actual experimental data.

An analytical effort was also undertaken to model the crack driving forces in a single crystal PWA 1422 alloy under fatigue crack growth loading conditions. The testing configuration analyzed was the Brazilian Disk Specimen, where various mixed mode crack growth extensions are achieved by inclining the crack relative to the compressive loading line. Two load angles were considered in this study: a 27° angle leading to a near pure Mode II test; and a 16° angle leading to a mixed mode load case. The variations of the anisotropic Mixed-Mode Stress Intensity Factors (K_I , K_{II} & K_{III}) with crack length were determined numerically using the Finite Element Method (FEM) for the tested load angles and crystal orientations. The differences between isotropic and anisotropic stress intensity factors (SIF) solutions were delineated. The experimental fatigue crack growth (FCG) rates were correlated with the anisotropic Mode I and Mode II SIFs. Furthermore, since the experimentally observed crack extension occurred along the $\{111\}$ facets, the experimentally measured FCG rates were correlated with a resolved shear stress intensity factor (K_{rss}) parameter originally proposed by Chen & Liu. Finally, the ΔK_{rss} parameter was shown to better correlate the experimentally observed FCG rates for the various tested crystal orientations than the Mode II parameter, as well as being able to predict the crystallographic crack path.

Third Generation Reusable Launch Vehicle

Analytical calculations were conducted to determine the thermal stresses developed in a coated copper-based alloy, Cu-8%(at.%)Cr-4%Nb (designated as GRCop-84), after plasma spraying and during heat-up in a simulated rocket engine environment. Finite element analyses were conducted for two coating systems consisting of a metallic top coat, a pure copper bond coat and the GRCop-84. The through the thickness temperature variations were determined as a function of coating thickness for two metallic coatings, a Ni-17%(wt%)Cr-6%Al-0.5%Y alloy and a Ni-50%(at.%)Al alloy. The residual stresses after low-pressure plasma spraying of the NiCrAlY and NiAl coatings on GRCop-84 substrate were also evaluated. These analyses took into consideration a 50.8 μ m copper bond-coat and the effects of an interface coating roughness. The through the thickness thermal stresses developed in coated liners were also calculated after 15 minutes of exposure in a rocket environment with and without an interfacial roughness.

Modeling studies were conducted on low pressure plasma sprayed (LPPS) NiAl top coat applied to an advanced Cu-8%(at.%)Cr-4%Nb alloy (GRCop-84) substrate using Ni as a bond coat. A thermal analysis suggested that the NiAl and Ni top and bond coats, respectively, would provide adequate thermal protection to the GRCop-84 substrate in a rocket engine operating under high heat flux conditions. Residual stress measurements were conducted at different depths from the free surface on coated and uncoated GRCop-84 specimens by x-ray diffraction. These data are compared with theoretically estimated values assessed by a finite element analysis simulating the

development of these stresses as the coated substrate cools down from the plasma spraying temperature to room temperature.

Lattice Block Fan Blades

A geometric model routine was created to generate a PATRAN neutral file to create the FEA model of a lattice block panel. The input parameters are the number of links spanning the length and width of the plate as well as the length of the individual links. Once a neutral file is created, a mesh is generated to model the lattice structure. A preliminary model using two-node beam elements was generated for a bend specimen oriented at 45 deg. to the plate orientation. The elastic-plastic material properties of 17-4PH stainless steel heat treated to 900F was assumed. Axial stresses as well as nodal displacements are calculated.

Sandwich Fan Blades

Work under the Ultra Safe Project at NASA Glenn Research Center encompasses research and development of advanced materials and structural design concepts to improve the state of the art for fan blades and engine containment. The goal of this sub-project is to provide safer, lighter-weight, and lower cost alternative fan materials as compared to the currently used titanium alloy or polymer matrix composite fans. The proposed material system is a sandwich fan construction made up of thin solid face sheets and a light weight metal foam core. The stiffness of the sandwich structure is increased by separating the two face sheets by the foam layer. The resulting structure has a high stiffness and lighter weight in comparison to the solid face sheet material only. The face sheets carry the applied in-plane and bending loads. The metal foam core must resist the transverse shear and transverse normal loads, as well as keeps the facings supported, separated, and working as a single unit. The material choice of the face sheet and the metal foam for this study is the aerospace grade stainless steel 17-4 PH. 17-4PH stainless steel is chosen due to its attractive mechanical properties and its ease of making foam through the powder metallurgy process of PORVAIR Inc. of Hendersonville, North Carolina. The advantages of a metal foam core are material isotropy and the ease of forming complex geometry such as fan blades as compared to typical honeycomb core structures. The foam material initially purchased from PORVAIR Inc. had a relative density of 6.0% and 80 pores per inch.

Part of the design process of any blade design is to determine the natural frequencies of particular blade shape. The designer needs to predict the resonance frequencies of a new blade design to properly identify a useful operating range his blade. Operating a blade at or near the resonance frequencies leads to high cycle fatigue which ultimately limits the blade durability and its life. So the aim of this study is to determine the variation of the resonance frequencies for an idealized sandwich blade as a function of face sheet thickness and core thickness, and foam density. The finite element method is used to determine the natural frequencies for an idealized rectangular sandwich blade. The proven Lanczos method to extract the natural frequency is used in the study. The variation of the resonance frequency with foam core thickness for a rectangular plate was determined for a 6.3" $\times$ 3.25" with a 0.1" constant face sheet thicknesses plate. The foam core assumed is a 17-4PH 80PPI with 6.0% relative density compared to a solid material. The first three modes corresponding to the first bending, first torsion and second bending modes, respectively, increase steadily with increasing the core thickness. The first mode increases from

around 160 Hz to 570 Hz by increasing the core thickness to 1.0 inch corresponding to a 247% increase in the frequency with only a 23% increase in weight. Hence the designer can easily increase the natural frequencies by just increasing the light weight core thickness. On the other hand, the results for varying the ratio of foam core thickness to the face sheet thickness to keep the overall thickness constant at 0.5" showed some unexpected results. For the first bending mode (Mode 1), the resonance frequency is almost constant. The second and third modal frequencies actually decreased sharply by introducing a foam core between the two face sheets, then starts increasing slightly with decreasing the face sheet thickness until they drop again when only the foam material is used. The observed trend can be explained as a competition between the effective stiffness of the system and the effect mass. By reducing the face sheet thickness the mass of the plate is reduced dramatically compared to the reduction in the stiffness, hence providing an increase in the frequency until the face sheet thickness is too small to provide any stiffness.

Crack Driving Forces in a Multilayered Coating System for Ceramic Matrix Composite Substrates

The effects of the top coating thickness, modulus and shrinkage strains on the crack driving forces for a baseline multi-layer Yttria-Stabilized-Zirconia/Mullite/Si thermal and environment barrier coating (TEBC) system for SiC/SiC ceramic matrix composite substrates are determined for gas turbine applications. The crack driving forces increase with increasing modulus, and a low modulus thermal barrier coating material (below 10 GPa) will have no cracking issues under the thermal gradient condition analyzed. Since top coating sintering increases the crack driving forces with time, highly sintering resistant coatings are desirable to maintain a low tensile modulus and maintain a low crack driving force with time. Finite element results demonstrated that an advanced TEBC system, such as ZrO_2/HfO_2 , which possesses improved sintering resistance and high temperature stability, exhibited excellent durability. A multi-vertical cracked structure with fine columnar spacing is an ideal strain tolerant coating capable of reducing the crack driving forces to an acceptable level even with a high modulus of 50 GPa.

A CAD Approach to Integrating NDE with Finite Element

Non Destructive Evaluation (NDE) is one of several technologies applied by the Life Prediction Branch at NASA Glenn Research Center to determine atypical deformities, cracks, and other anomalies experienced by structural components. NDE consists of applying high quality imaging techniques (Such as x-rays and Computed Tomography (CT)) to discover hidden manufactured flaws in a structure. An effort is in progress to interconnect NDE with the finite element (FE) computational method to perform detailed structural analysis of a given component including the observed flaws as depicted by the NDE technique. A methodology was discovered to incorporate NDE observation into an FE analysis as closely as feasible. A detailed demonstration showing the analytical steps used to exercise this procedure is outlined in a NASA TM. The method consists of using the image processing software Velocity², a CAD base software Rhinoceros 3D, and the MSC/Patran finite element graphical processing package to re-construction a 3-D model of a component using a series of CT scan images. Key elements detected by NDE such as manufacturing anomalies and structural deformities in a structure were modeled to match their

actual shape as detected. The procedure applied in constructing a 3D volume remains somewhat cumbersome. Automation of the features utilized to reduce the number of sequences required is planned to be implemented in the near future.

Residual Stress effects on Disk Life

Gas turbine engine disks are routinely shot peened in an attempt to improve their fatigue lives. Shot peening induces compressive residual stresses in the surface which inhibits or significantly delays the initiation and early growth of surface fatigue cracks. A study was to investigate the effects of flight hours on this beneficial compressive residual stress. Residual stress profiles were measured by X-ray diffraction in two shot peened gas turbine engine disks with significantly different flight hours. Analyses were performed to compare the residual stress and cold work profiles as functions of depth at several critical locations on each disk. Shot peened sections of one disk were also extracted and further exposed to various combinations of time and temperature. The compressive stress did not deteriorate significantly during service for up to 500 flight hours, and were also resistant to temperature exposures up to 1,200 °F. Higher temperature exposures allowed significant relaxation of the compressive residual stresses, which could presumably reduce or even eliminate their beneficial effects on the component fatigue life.

A Combined NDE/Finite Element Technique to Study the Effects of Matrix Porosity on the Behavior of Ceramic Matrix Composites

Ceramic matrix composites are being considered as candidate materials for high temperature aircraft engine components to replace the current high density metal alloys. Ceramic Matrix Composites (CMC) are engineered material composed of coated 2D woven high strength fiber tows and melt infiltrated ceramic matrix. Matrix voids are common defects generated during the melt infiltration process. The effects of these matrix voids are usually associated with a reduction in the initial overall composite stiffness, and a decrease in the thermal conductivity of the component. Furthermore, the role of the matrix as well as the coating is to protect the fibers from the harsh engine environment. Hence, the current design approach is to limit the design stress level of CMC components to be always below the first matrix cracking stress. The stress concentrations around observed macroscopic matrix voids are calculated using a combined NDE/Finite-Element Scheme. The Computed Tomography (CT) is utilized as the NDE method to characterize the initial macroscopic matrix void's locations and sizes in a CMC tensile test specimen. The Finite Element is utilized to calculate the localized stress field around these voids based on the 2D CT images. The same specimen was also scanned after tensile testing to a maximum nominal stress of 150 MPa to depict any growth of the previous observed voids. The post test CT scans depicted an enlargement and some coalescence of the existing voids.

Unfolding the Ceramic Inclusion Size Distribution in a Powder Metallurgy Alloy from Planar Section

Non-Metallic inclusions are inherent anomalies introduced during the powder metallurgy production process of nickel-base superalloys. These inclusions are well known to degrade the component fatigue life. Modern nickel disk powder processing facilities have successfully reduced the levels of inclusions to less than 1 part per million by weight. But due to the huge

volume of full size components, the probability of having a life limiting critical inclusion in a component is still a concern. A task was undertaken to study the effects of inclusion size on fatigue life by artificially seeding production quality nickel base superalloy powder. The seeded powder was processed into disk forgings using conventional turbine disk production processes (such as hot compaction, extrusion, and isothermal forging). The seeds, much like the natural inclusions, were alumina particles screened at various mesh sizes typical of production powder.

The effect of processing on the seeded inclusion size distributions was determined before and after processing since extrusion and forging can have a drastic effect on the final size and orientation of the inclusions from inclusions break ups and alignments. The approach taken here was to use metallography and image analysis to characterize the inclusion size distributions on three orthogonal planes in the final forging. Stereological unfolding of the 2D metallographic distributions was then used to determine the volumetric size distribution. These results are compared to the initial seed size distribution prior to processing.

Publications

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“A CAD Approach to Integrating NDE with Finite Element,” Ali Abdul-Aziz, James Downey, Louis J. Ghosn, and George Y. Baaklini, NASA TM, September 2003.

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"A Computer Code for Gas Turbine Engine Weight and Disk Life Estimation," Michael T. Tong, Ian Halliwell, and Louis J. Ghosn, Proceeding of the TURBO EXPO 2002, ASME Turbo Expo: Land, Sea & Air 2002, June 3–6, 2002, Amsterdam, The Netherlands GT-2002-30500.

"Residual Stresses in Thermal Barrier Coatings for a Cu-8Cr-4Nb Substrate System," Louis J. Ghosn, and Sai V. Raj, NASA/TM-2002-211561, July 2002.

Presentations

"Crack Driving Forces in a Multilayered Coating System for Ceramic Matrix Composite Substrate," Presented at the 29th International Conference on Advanced Ceramics & Composites, January 23–28, 2005, Cocoa Beach Florida.

"Unfolding the Ceramic Inclusion Size Distribution in a Powder Metallurgy Alloy from Planar Section," Presented at the Materials Science & Technology 2003 Conference, November 9–12, 2003, Chicago, Illinois.

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"Fatigue Crack Driving Forces in PWA-1422 Single Crystals Subjected to Mixed-Mode Loading," Presented at the USAF 2001 ASIP conference, December 13, 2001, Williamsburg, Virginia.

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